STUDIES ON THE STABILITY OF SOIL STRUCTURE: INFLUENCE OF MOULDS AND SOIL FAUNA

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INTRODUCTION

THE INCORPORATION of organic matter into the soil can have repercussions of variable importance and, sometimes, contradictory consequences on its physical properties. Because of the interactions between different phenomena in the soil, their study in one set of natural conditions does not permit an appreciation of their result in those of another environment and cannot, therefore, provide evidence of their mechanisms.

In the laboratory, by contrast, it is possible, by adequate control of experimental conditions and by isolating the factors susceptible to intervention, to fix in a more precise fashion, and to define more completely, the effects of the added organic substance. These investigations, which represent to some extent models of natural phenomena, have as their aim the definition of the principal trends. Comparison of the results thus obtained with those of observation and experiment in the natural state permits one to verify that the mechanisms isolated in the laboratory are really fundamental and not an artefact of the particular conditions of the experiment.

This approach has been applied to a study of the action of organic matter on the structural stability of soil, either as a direct effect or through the intermediary of certain elements of soil fauna.

Definition and meaning of structural stability

At any one time the structure defines the manner in which the elementary constituents of the soil are disposed in relation to each other. The structural stability expresses the resistance of this arrangement to the action of water as the principal agent of degradation.

Hénin (1938) advanced a theory of the degradation of structure which constitutes a synthesis of the hypothesis of Yoder (1936), the shattering of soil aggregates, and that of Schloesing (1855) of the dispersion of colloidal cements. The scheme proposed presented a double advantage: first it has been possible to verify the consequences experimentally by very different procedures, which strengthens its claim to validity; secondly, it has permitted the institution of a series of tests which allow the assessment of structural stability in the laboratory. Taken separately, these tests show the influence of the two principal factors of stability (cohesion of the moist soil and wettability of dry soil). Their result, regrouped in one index, is in good agreement with the behaviour of the soils *in situ*.

In this work Hénin's theory has been used as a basis for the interpretation. The method to control the modifications of stability arose in the course of the attempt.

The method developed consists of shaking on 0·2 mm sieves, under water and in standard conditions, samples of less than 2 mm average diameter (Hénin and Monnier, 1956). Previous to wet sieving the samples are allowed to imbibe an organic liquid (ethyl alcohol or benzene) which modifies the action of the water. This gives a measure (*a*) of aggregates stable after pre-treatment with alcohol (Ag_a, per cent), which varies according to the cohesion of the moist soil; (*b*) of the aggregates stable after pre-treatment with benzene (Ag_b, per cent), the variations of which reflect the modifications of the wettability of the soil. The results of these two tests, and of others which are difficult to interpret in isolation, are used in the elaboration of an overall index of stability.

DIRECT ACTION OF ORGANIC SUBSTANCES ON THE STABILITY OF SOIL STRUCTURE

The aim of the experiments

The decomposition in the soil of vegetable material leads in the first phase to the formation of transitory products of humification. The experiment described here had as its aim the precise action of the substances on the stability of the structure. Variations were made in the nature of the vegetable material and the conditions of aeration. It also appeared of interest to be able to judge separately the efficiency of the products fixed immediately on the soil at the point of formation, and that of the substances that have migrated. Finally, it was necessary to obtain, for each combination of the three preceding conditions, a series of measurements of the quantities of newly fixed substances that would be sufficiently extensive to allow by statistical

study the establishment of quantitative relationships between the concentration of the active material and the diverse forms of stability.

Experimental details

For this work glass tubes, of 5 cm diam. and 20 cm long, were filled with a sample of aggregates, graded (0·2–2·0 mm) from a clay loam poor in organic matter (0·3 per cent carbon), and separate columns were filled with samples of these aggregates in which 2 to 10 per cent of a finely ground vegetable material, lucerne hay, wheat straw and oat straw, respectively, had been mixed. The columns were then carefully wetted by capillary imbibition and drained. *Figure 1*

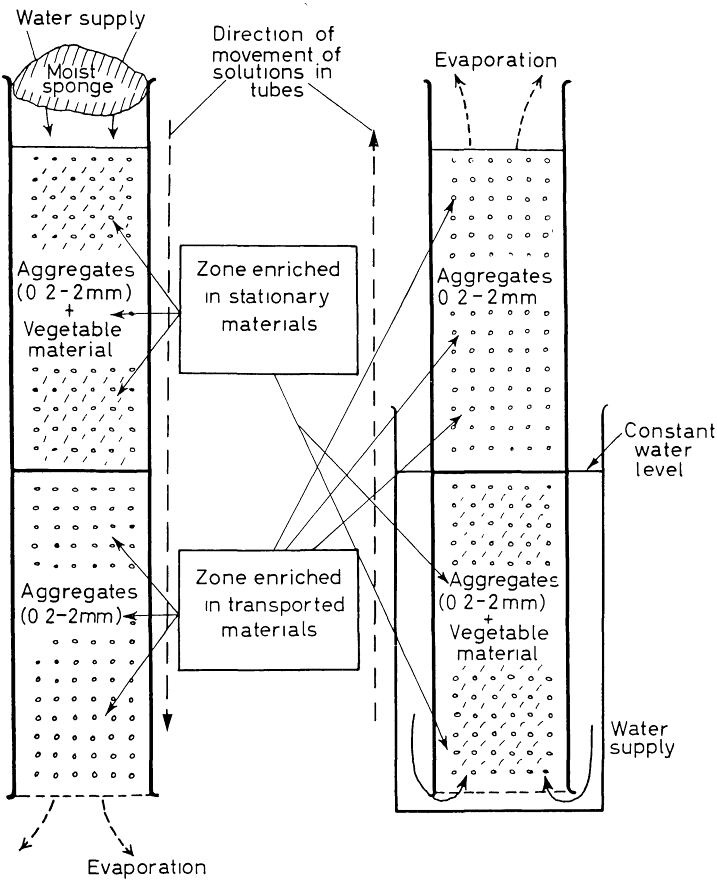

Figure 1

shows the arrangements for both aerobic and anaerobic fermentation and the possibilities that they offer for isolation of the factors operating. In addition, for the aerobic tubes, humidity is maintained constant throughout the duration of the experiment by the daily application of water to the upper part of the tube, and the level of water of the anaerobic tubes is adjusted every day by additions to the outer vessel.

The experiment was continued in this fashion for $2\frac{1}{2}$ months to ensure sufficient decomposition of the various vegetable materials used; after decanting, the columns are fractionated in successive slices which contain, in varying quantities, in one group a residue arising from the various vegetable materials added and the fermentation products remaining *in situ*, in the others the fermentation products that had moved, the products varying according to whether fermentation had taken place in an aerobic or anaerobic environment.

Samples of each layer are submitted to sieving under water, and for those which contain the vegetable material, a densimetric fractionation of the organic matter was made (Hénin and Turc, 1949). This is done by centrifuging the sample in an organic liquid of suitable density (a mixture of carbon tetrachloride and bromoform of sp. gr. 2·0) in which the organic matter that is not bound to the supporting mineral floats to the surface because of its lower density. The quantity of carbon in the dense fraction provides an estimate of the quantity of substances which are fixed to the soil during the course of the experiment.

Results

The extent to which the different plant materials contributed to the bound organic carbon is shown in *Table 1.*

It can be seen that the quantities of substances formed are on the average greater from lucerne hay than from wheat straw or oat straw.

Table 1

Comparison of the average carbon content of the soils according to the nature of the added plant material

		No addition	*Lucerne hay*	*Wheat straw*	*Oat straw*
Products fixed in place of origin	aerobic	3·8	17·1	9·1	11·8
	anaerobic	3·9	16·2	7·2	6·9
Transported products	aerobic	4·0	8·0	5·0	4·9
	anaerobic	3·9	8·7	5·2	4·8

It would appear that the C/N ratio of the added material is the factor determining the intensity of decomposition, but the greater fineness of the oat straw does not appear to have caused its decomposition to be any more vigorous than that of wheat straw.

By contrast, the *specific efficacy* of the substances formed on the stability of the structure showed itself to be independent of their origin, as shown in *Table 2* where, without prejudging the possible relation between carbon content and stability, the values Ag_a per cent and Ag_b per cent obtained are compared on the basis of samples containing similar quantities of the newly fixed substances that have arisen from the decomposition of the different plant materials studied.

Table 2

Comparison of the efficacy of the substances produced from different plant materials (fixed products only)

Conditions of fermentation	*Plant material*	C	Ag_a	Ag_b
			per cent	
Anaerobic	lucerne hay	7·45	38·0	52·0
	wheat straw	7·45	40·0	51·4
	wheat straw	5·5	24·0	32·6
	oat straw	5·6	28·2	33·2
Aerobic	lucerne hay	10	50	74·0
	wheat straw	9·2	49	70·4
	oat straw	9·5	55	69·0
No treatment	nil	3·8	16·0	3·0

The newly bonded organic matter has not enhanced the cohesion of the moist soil (Ag_a, per cent) until a threshold value in the neighbourhood of 7 per cent carbon is reached. Beyond this threshold, changes have remained relatively small, of the order of an additional 2·5 per cent of Ag_a per cent per 1 per cent carbon fixed by the soil.

The action on the wettability of the soil, by contrast, is much more important. This shows itself in the very small quantities of substance fixed necessary to give rise to an appreciable increase in the weight of aggregates stable after pre-treatment with benzene, which marks a diminution of wettability.

The fixed products have a very high specific efficacy. Regression analysis shows that, for carbon contents between the limits of 5 and 9 per cent, each unit of carbon fixed increases the Ag_b per cent by 13 and 17 per cent in aerobic and anaerobic conditions, respectively.

The transported products, whether produced aerobically or anaerobically, have not enhanced significantly the stability of the aggregates (5–6 per cent increases in Ag_b per 1 per cent C).

Comparison of these results with those of other experiments leads one to attribute to iron, combined with these substances by the formation of organo-ferrous complexes in a reducing environment, an important role in the manifestation of the hydrophobic nature of certain organic materials.

INFLUENCE OF SOIL FAUNA ON STABILIZATION OF STRUCTURE BY ORGANIC MATTER

In another series of experiments, an attempt has been made to define the precise role that could be played by certain elements of the soil fauna (Jeanson, 1961, 1963) in the phenomena of stabilization by organic matter (Jeanson, 1960).

The tubes used were of the same construction as in the preceding experiment, but the ground lucerne hay was localized in certain parts of the column. The latter was moistened by capillarity from a layer of water maintained at a constant level at the base of the tube. Each tube received two worms of known species (*Lumbricus terrestris* Linné) whose growth and breeding were followed during three months.

Table 3

Relationship between bound carbon and the cohesion and wettability of soil and worm casts

	Initial state	*Worm casts*	*Unworked soil*
Bound carbon	100	170	152
Cohesion (Ag_a, per cent)	100	83	85
Wettability (Ag_b, per cent)	100	141	110

The casts ejected by the worms on the surface were collected, and their stability and content of organic matter were compared to those of the part of the soil not worked by the animals or where only microbiological decomposition had occurred.

In *Table 3* each characteristic is represented by an index constructed from the average results obtained. The base value of 100 corresponds for each characteristic to its value at the start.

The Table shows that the casts have a stability after benzene pretreatment that is significantly higher than the parts of the soil not worked by the worms. By contrast, after treatment with alcohol the stability is unchanged. The greater content of bound carbon in the casts provides an interpretation of the phenomena. The earthworms influence the stabilization of structure by assuring the mixing of fermentable organic matter with the soil. As a consequence, the soil which passes through the digestive tract shows an increase in its content of difficultly wettable substances. By contrast, it does not appear that the mechanical action of mixing is of any consequence on the cohesion of the wet soil.

These casts are thus no more stable than the soil from which they are formed, except in proportion to the increase in organic matter that they have received. The action of the worms is thus much more intelligible and follows from the localization and concentration of the organic matter: they themselves are solely responsible for the mixing.

DISCUSSION

The principal conclusions of this work can be related to the phenomena observed in natural conditions. In particular, the importance of the intimate mixing of the added organic matter with the materials to be stabilized, which follows from the very superior specific efficacy of the products fixed to the soil at the site of formation, provides the explanation why the stabilization of the soil through the intermediary of the root system of the forage grasses is much more marked than that which follows the incorporation into the soil of other forms of organic matter.

Extracted from the soil and placed so as to ferment in contact with a sample of earth, these roots do not, however, show any particular efficacy, which confirms the non-specificity of their origin. It is the excellent distribution in the soil of these fine fascicular roots which ensures during the course of their decomposition a regular covering of the aggregates of soil by the very active but non-mobile products that are to be found, and the explanation of the effect that they produce. Cereal straw, on the contrary, is so badly mixed in arable land by the currently practised techniques for burying it that the action of the most active product of its decomposition cannot be seen.

The action of the soil fauna, and particularly that of the earthworms, must equally be related to the notion of mixture of the organic matter. The addition to the soil of fresh organic matter promotes an increase in the number of earthworms and of their activity. This has two principal consequences. First, the perforation of the soil by

galleries having walls impregnated with organic matter and, consequently, more resistant to the action of water, of itself improves the structure. Furthermore, the intimate mixing by the animals of the organic debris of the soil results in a marked stabilization of the structure. This aspect of the activity of the Lumbricidae is particularly clear at the time when straw or manure is buried in the soil.

It has been shown that a study on models permits, by isolation of representative factors, the separation of the principal mechanisms for stabilization by organic matter. Examined in the light of these results, the complex phenomena which arise in natural conditions are better understood, and in particular the proper role of each of the factors which are simultaneously affected by a modification of the situation can be precisely defined.

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DISCUSSION

OVINGTON commented on the lack of attention to the effects of large animals. He felt that in parts of East Africa, elephants, by their habit of blowing soil over their backs, must play some part in ensuring widespread mixing and distribution of the microflora.

EDWARDS commented that each of the papers had stressed that soil, far from being something static, was a biological entity, and asked JACKS whether he could give some time scale to the processes he had described. JACKS replied that he knew of no measurements of the progress from one stage to the next; most of the reports were based on observations of existing conditions on mountains, but one worker had suggested 50 years to reach the grass stage from the time when lichen formation started. When considering a fresh deposit, such as a sand dune, a good profile could be developed in 30–40 years, and soil formation on volcanic lava in the tropics was even more rapid. YAALON disagreed with some of the Russian findings on the stages of soil development from lichens and mosses, since he felt that the high mountain soils which had such vegetation were in a steady-state condition with their environment and would remain so for thousands of years, provided the climate remained constant; the same applied to many lithosolic soils on steep slopes. In general, there was development of soils with landscape, and the spatial differentiation of the soils of hill slopes was a more or less steady condition. On desert pavements in Israel,

there were lichens which would probably stay there indefinitely; they developed on flints and contained considerable amounts of chlorine and bromine in the same ratio as in rainwater, from which these elements were presumably derived. JACKS thought that mosses would normally succeed lichens, but it could be a very slow process, and it might take tens of thousands of years before enough fragments accumulated to give microsoil development.

BURGES felt that debate of the merits of alternative views of soil development—the stable state and progressive succession theories—was not very profitable, since so much depended on the area considered. In Western Europe there had been a tremendous upheaval accompanying the last Ice Age, with areas of rock and raw soil exposed to form the raw material for a sequential pattern of soil development. In areas of more mature topography and soil development, such as parts of Australia, the successional development of soil was quantitatively unimportant; the bulk of the samples examined were virtually static and held in dynamic equilibrium in one of the very early stages of the succession.

DAVIES reported that examination of lichens found in Snowdonia and growing on quartz masses produced analyses comparable with the composition of the dust which fell from the atmosphere; those which grew on basic igneous or tuffaceous rocks reflected the composition of the rock itself. In the first case, the lichen existed on aerial matter, and in the second on material it was causing to be released from the stone.

EDWARDS, referring to the papers of VAN DER DRIFT and HEATH, enquired how they would assess the relative importance of different groups of animals in litter breakdown and soil formation. HEATH replied that in the tropics it seemed that when the forest was cleared, the mound-building termites rather than the humus feeders were more important in breaking down litter, but this was only based on eye estimates of colony abundance. Mites, which also abounded in tropical soils, might likewise be of some importance. In temperate agricultural soils, earthworms were regarded as dominant in breaking down litter, releasing nutrients and affecting soil structure, and though smaller animals—collembola, mites and enchytraeid worms—were also vital in the breakdown cycle, he doubted whether they influenced structure to any great extent. VAN DER DRIFT said that experimental study of the relative importance of different groups was difficult, but there were two methods. The first was by breeding animals and observing what type of food they took and at what intensities they attacked it, but breeding experiments were very far from natural conditions. The second method was by studying profiles, since the excrement of many animals was rather stable, and knowing the morphology of those excrements it was possible by the examination of thin sections of soils and direct microscopical observation to discover which animals had been active. This method could give the relative importance of the larger groups of animals—enchytraeids, collembola, oribatid mites—and had shown, for example, that the larger arthropods were more important in mull sites while the micro-arthropods were dominant in mor sites. NYE reported that experiments had shown that 10 tons of straw applied to the soil in tropical savanna regions disappeared in two months, in association with intense termite activity. Such a treatment applied in Britain would induce nitrogen deficiency, but the fact that this did not happen in the tropics might be associated with a different microbiological breakdown of the straw when it had been comminuted by the termites.

GREEN was surprised that so little weight had been given to the possible importance of ants in temperate soils. In undisturbed grassland in Romney Marsh there was a frequency of ant mounds quite equal to termite mounds which had been reported; they accounted for 15 per cent of the soil surface. Measurements had shown that the ants had had a marked influence on sub-soil porosity and structure, particularly between 15 and 36 in.; the volume of material which had been raised to the surface must have a profound effect on soil formation. HEATH thought that ants might be dominant in areas of high water table and lower pH which would be unfavourable to earthworms. If conditions were

improved, the ants would probably be supplanted by earthworms. BURGES referred to the turnover of litter in subtropical rain forests in New South Wales by bush turkeys and bower birds; it had been found that each square yard was effectively turned over every three weeks, and in this country blackbirds and such large animals can contribute significantly.

JENNY described the existence of a vesicular layer to a depth of about 6 in. in some American desert soils; the structure was poor, there were no earthworms and very little vegetation. A second point he made related to an abortive experiment where a brunizem soil with good structure had been puddled thoroughly, and to it manure had been added. After inoculation with earthworms the worms had died; JENNY queried whether their presence was really the cause of good structure or vice versa. HEATH thought that the vesicular structure of the desert soils might be due to the activities of cicada nymphs. With regard to the use of worms to improve poor soil structure, he said that cocoons of a species which lived in compost heaps, *Eisenia foetida,* had been sold with this aim in view, but when they were applied to mineral soil they did not survive. JENNY admitted being a victim of commercial enterprise! HALLSWORTH referred to an experiment on the use of earthworms as an aid to the reclamation of tough clay subsoil left at the surface after ironstone working in Northamptonshire. Application at rates of 600,000 worms per acre had produced appreciable crumb structure after three years. With these high rates of inocula, farmyard manure had disappeared in three to six months; without worms, much of the manure remained on the surface two years later. Obtaining a supply of worms on a sufficient scale was a major problem, since in this experiment the build-up of population in the field was slow; *Lumbricus terrestris* and *Allolobophora longa* seemed to thrive on the heavy clay, even though their burrows only penetrated to about 80 cm below ground.

VAN DER DRIFT described a successful inoculation of reclaimed polder soil under grass in an orchard; at the area of release of several hundred surface-living earthworms, *Allolobophora caliginosa,* the grass mat was dispersed and a crumbly structure developed; after a few years this spread over about 100 m radius, but much depended on the species which was introduced.

EDWARDS brought forward the problem of the stages of the breakdown of leaf litter; he quoted BURGES' paper to the effect that fungi and other microorganisms were of primary importance in the newly fallen leaf, and said he had the impression that VAN DER DRIFT also thought that such organisms acted immediately. His own work, however, suggested that the situation was not so clear-cut and he believed many microorganisms were unable to act on the litter until the soil animals had fragmented it very considerably. In the complete absence of animals, could fungi break down litter completely? What happened to leaf litter as it passed through the earthworm? OVINGTON said that he, too, wondered whether the significance of animals lay in terms of mechanical breakdown of the tissue or a chemical change, or a combination of the two. The time of passage through an animal seemed almost too short for much chemical change. VAN DER DRIFT was fairly certain that soil animals did not attack fresh litter, but after exposure to natural conditions, during which time the leaves were subject to microbial attack and leaching with water, they would be taken. The main microorganisms on freshly fallen leaves brought about superficial changes and attacked the binding substances between the cells; they were restricted in their capabilities but prepared the leaves for further attack by animals, and these in their turn would leave the litter ready for a new population of microorganisms. He thought that the most important effect of animals was in terms of mechanical breakdown; comparison of the chemical composition of the excrement of certain animals with the leaf material they consumed showed very little change, but it was most important to recognize that many animals are selective in their feeding, and useless to compare whole leaf composition, including veins, etc., with excrement. This was important because the changes occurring during passage through the animal were only minor and mainly affected the small amount of easily decomposable carbohydrates.

NYE asked whether microorganisms present in the gut broke down litter during its passage through earthworm, or whether they were mixed in during comminution, and decomposition proceeded after excretion. HEATH felt that the grinding together of the soil and organic matter was most important, since in this way fresh surfaces were exposed to microbial activity; Tracey had reported the occurrence of the enzyme cellulase in the gut of earthworms and Parle had also reported a rich development of actinomycetes in their bodies.

DIMBLEBY referred to 15-year-old experiments on the heaths of N.E. Yorkshire where he was trying to reproduce the ecological succession by applying birch litter to the heath surface. One immediate result had been a change in the soil fauna; small earthworms, *Bismastus eiseni*, had come in and there had been an increase in the enchytraeid worm population. It had been mentioned that Dendrobaena was a species able to mix mineral matter with organic matter, but he had found them living almost exclusively in the humus layer and he wondered what would induce them to start mixing raw humus with the mineral soil underneath. VAN DER DRIFT's suggestion that worms appreciated a variety of diet was interesting, and it might be that the reason they disliked raw Calluna humus was the monotony of having nothing else to eat. DIMBLEBY asked whether, if birch litter were mixed with Calluna raw humus, they would eat the Calluna litter as well or confine their attention to the birch litter. VAN DER DRIFT replied that Dendrobaena occurred mainly in superficial litter layers, together with many species of enchytraeids; only if *Lumbricus rubellus* or *L. castaneus* were present would he expect mixing of mineral and organic layers. He had found that Calluna material was only rarely attacked by soil animals, but if given a very uniform diet, experience showed that they would take material which they would otherwise reject.

HALLSWORTH referred to EVANS' observation that earthworms reproduced more rapidly when fed on cow manure than on the grass from which it originated, and said this suggested the possibility that worms had a high requirement for vitamins of the B group. This was one aspect of earthworm physiology which had not received much attention, nor had there been any detailed specification of the nutritional requirements of soil animals. It was barely adequate to say that worms had been fed on beech or alder leaves, since not only did the composition of these vary according to the portion consumed but, as DAVIES's group had shown at Bangor, the composition of beech leaves varied remarkably with the ground on which they were grown. HALLSWORTH also pointed out that there was scope for the study of effects of microclimate on the persistence of excrement in and on the soil; the length of time during which it remained as an independent entity would be affected by the variation of temperature and humidity in the litter layer. VAN DER DRIFT replied that he had not studied the effect of microclimate, but in woodlands he had found that excrement in the litter layer of mor sites persisted very much longer than similar material in the mineral soil of mull sites.

EDWARDS remarked that the paper by JEANSON and MONNIER showed how quite simple experiments could provide valuable answers, and another feature had been the importance of cooperation between diverse specialists. HÉNIN pleaded for due attention to be paid to the analysis of phenomena in the field and quoted the difficult case of the problem of the effect of structure on the growth of plants; it would be possible to set up experiments in which the air content was systematically varied, but an experimental assessment of microbial action would be difficult to devise. A succession of factors was involved. NYE thought that HÉNIN's failure to find any effect on soil structure when grass roots were added was due to the omission of the physical factor of root pressure necessary to squeeze clay particles together to give stable aggregates. HÉNIN felt that root pressure was not the only factor involved: one could get very loose aggregates which were quite stable, provided organic matter was present. He thought that the dominant factor was the reduction of wettability by the organic matter so that, when the aggregates were moistened, the pressure of penetration of the water within was modified.